The NOvA Near Detector

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Presentation to the NOvA Working Group

20 February 2007

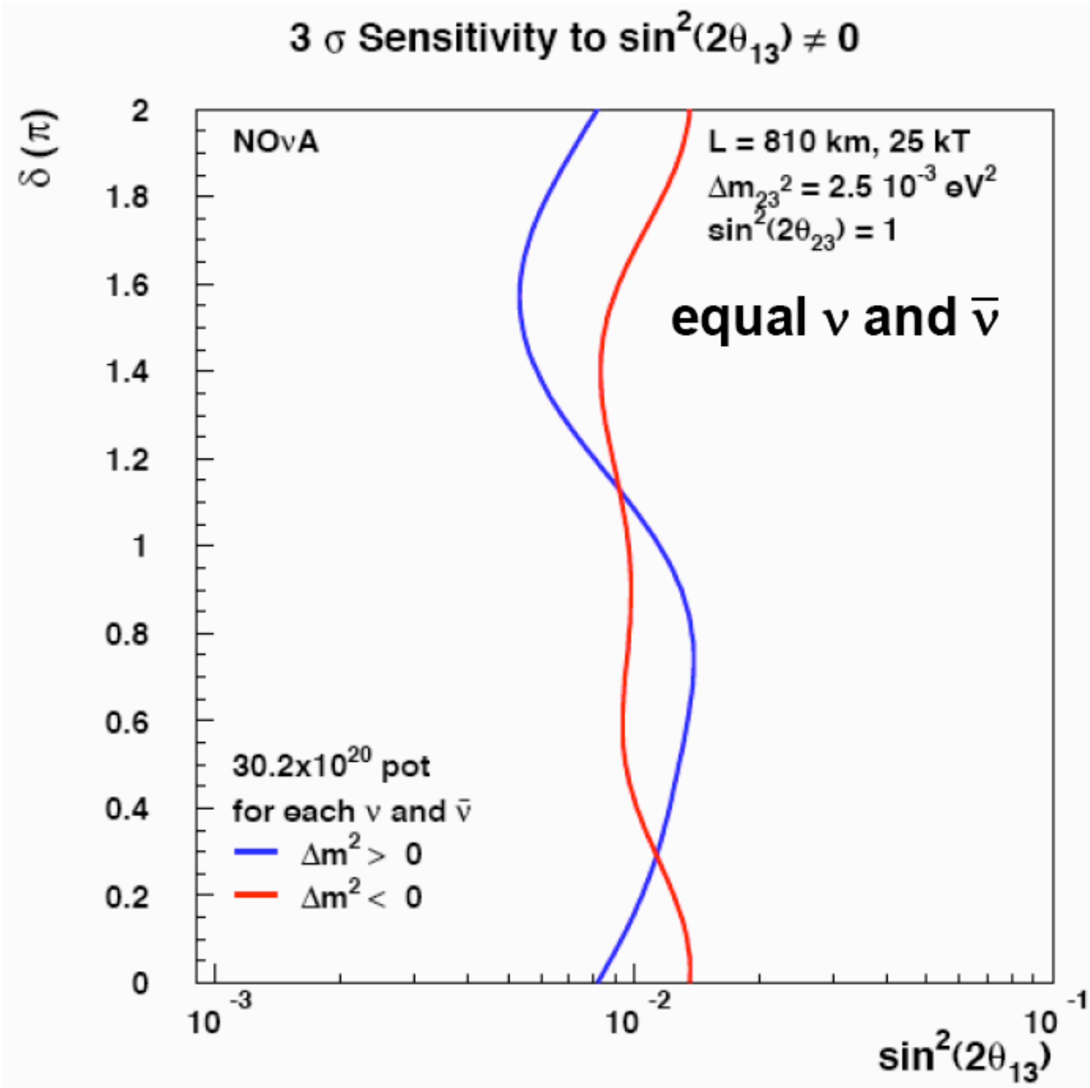
Outline of this presentation

1. Review of the role of the near detector in the NOvA experiment
   1. I will focus on the roll played in the ν_e appearance measurement
   2. Plays roll in ν_μ CC disappearance measurement but I will spend less time on that
2. Important near detector design parameters
   1. Location
   2. Size
   3. Orientation

ν_e appearance search

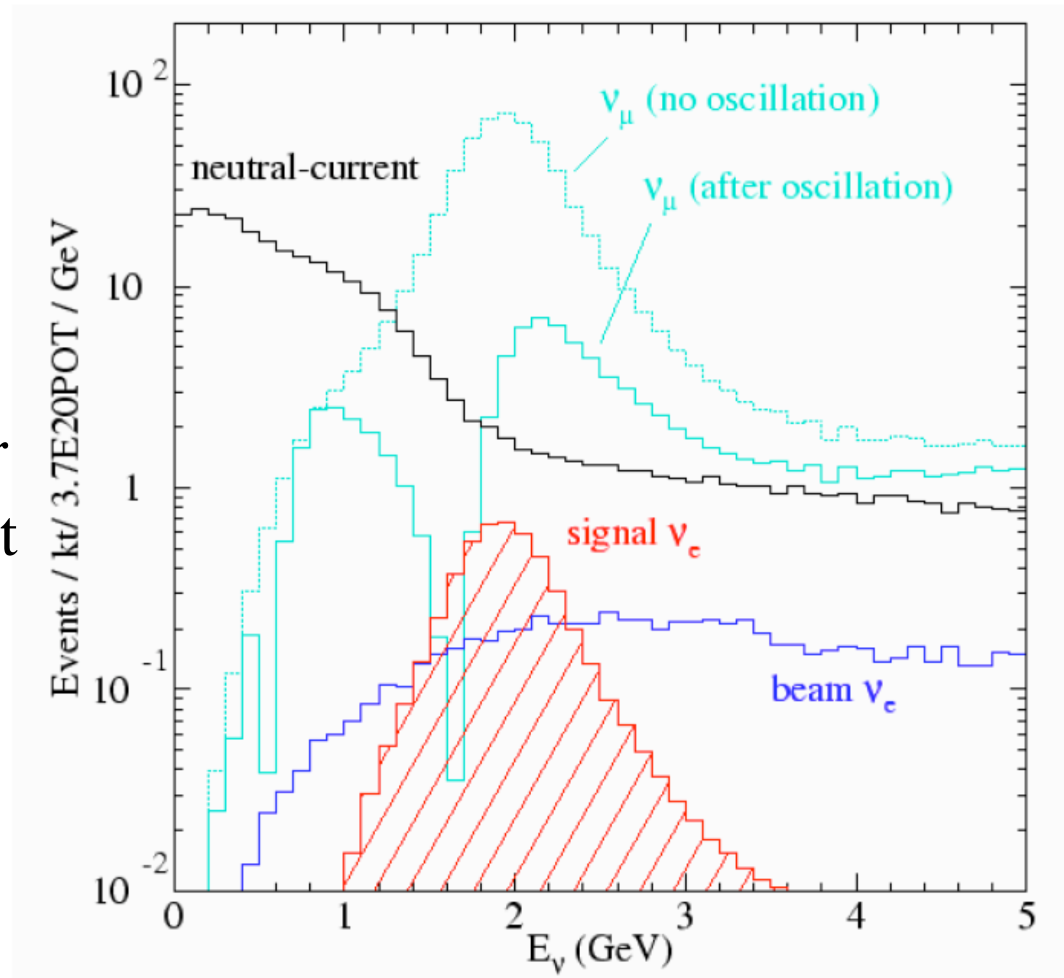
- NOvA's primary goal is to extend the search for ν_μ-ν_e oscillations a factor of 10 beyond results expected from MINOS
- Look for excess of ν_e CC-like events over backgrounds at far detector

$$FOM = \frac{N_s}{\sqrt{N_b}}$$



Background sources for ν_e appearance search

- To push backgrounds down to level of intrinsic ν_e requires:
  - 50:1 rejection against ν_μ CC at far detector *500:1 at near detector*
  - 100:1 rejection against NC
  - Power to reject the beam ν_e comes from energy resolution
- Need to characterize detector performance well



Statistical unfolding background from signal

ν_e **CC signal**

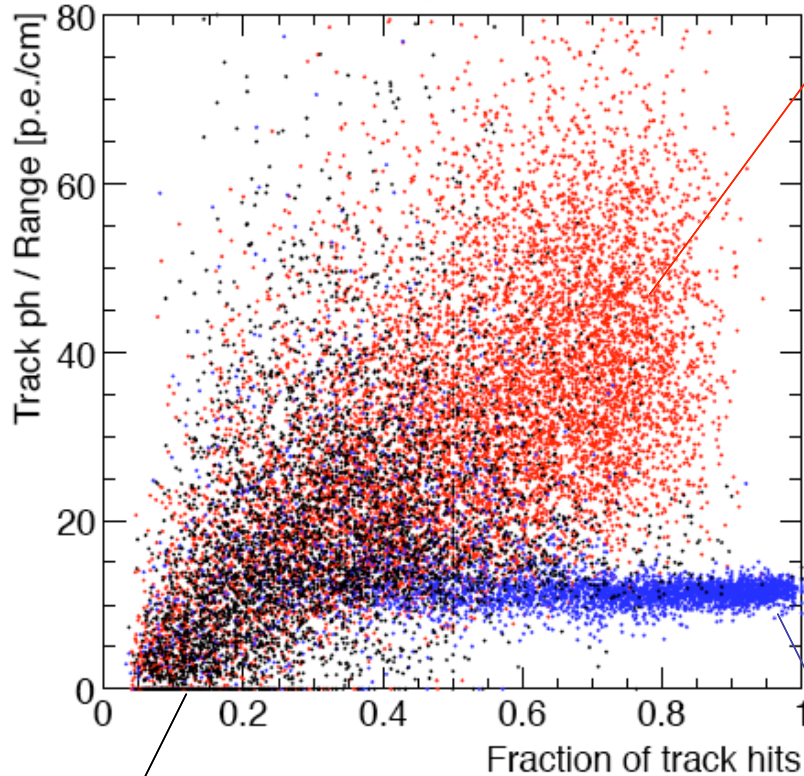
ν_μ **CC**

NC

To do ν_e CC event tagging NOvA looks at ~15 event shape variables in an artificial neural network. 4 plotted here.

Fraction of hits in track vs. track ph/range (at center)

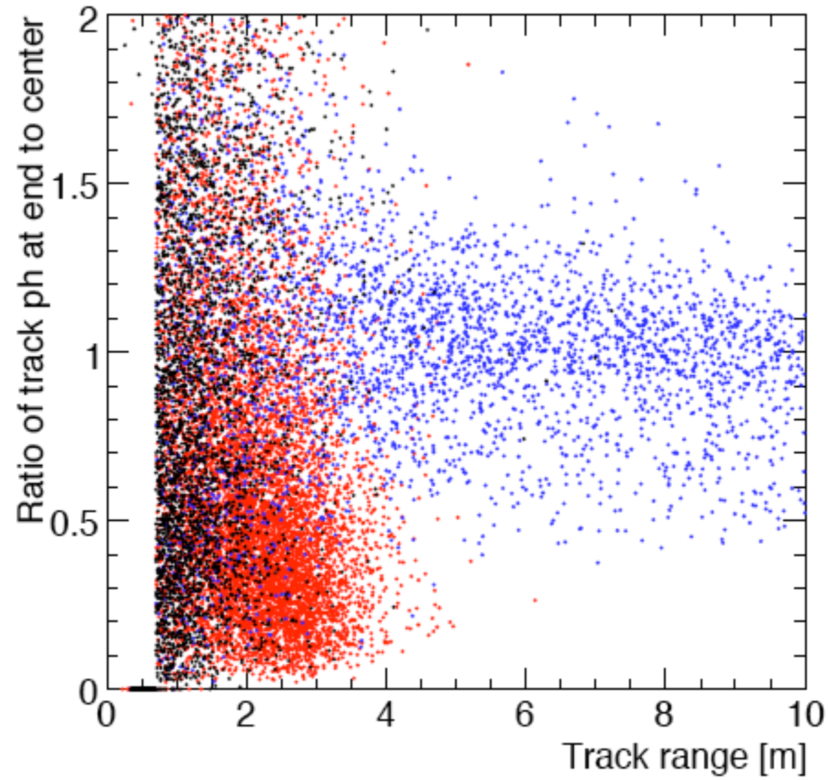
electrons



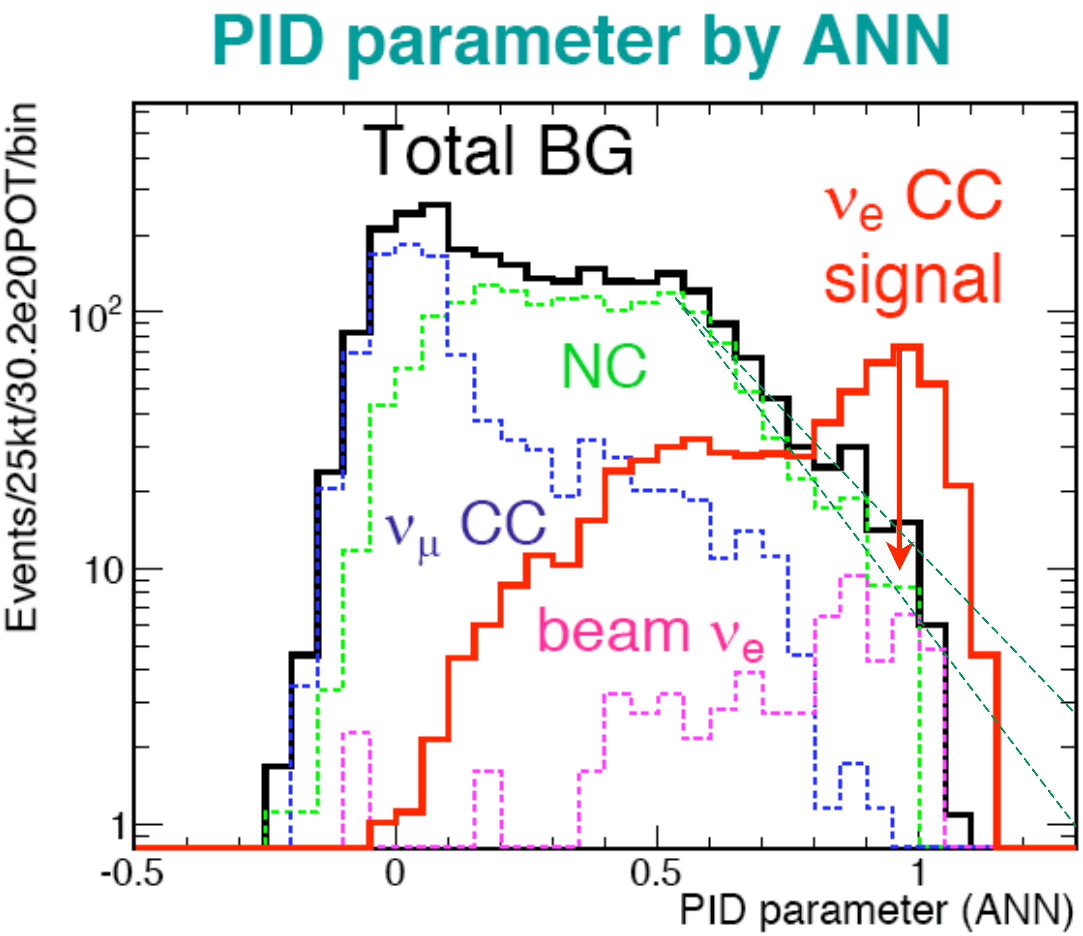
neutral-current

muons

Track range vs. track ph at end / ph at center



Particle ID performance

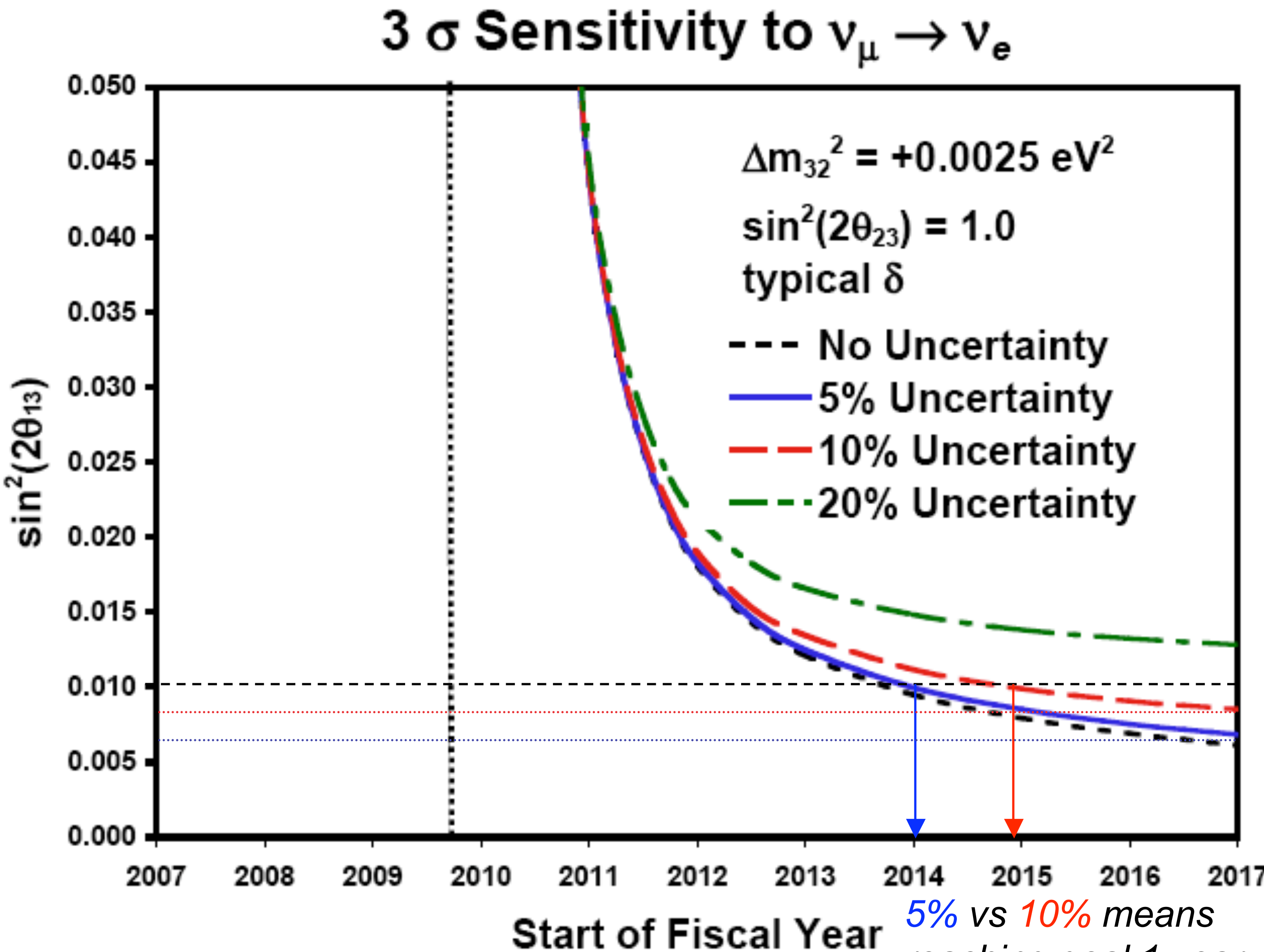


	Eff.[%]	# accepted
ν_e signal	28.8 (28.7)	208.7(163.2)
BG	0.38 (0.39)	32.3 (32.8)
NC	0.24	15.1
ν_μ CC	0.08	1.7
ν_e beam	9.47	15.5

Numbers in parentheses are for w/o matter effect.

- Calculations shown for CHOOZ limit
- Goal of experiment is to push limit x10 beyond: 16 signal events over a background of 33 events
- Background comes equally from NC and beam ν_e
- Small changes make a big difference: Changing NC rejection factor according to the dotted lines at left increases the background by a factor of two

Uncertainty on background



(old, technically limited schedule)

20% uncertainty fails to meet goal

5% vs 10% means reaching goal 1 year earlier

Sources of uncertainty in background

- Flux
- Cross-sections
- Detector response (NC ⏩ν_e-CC fake rate, ν_μ-CC ⏩ν_e-CC fake rate, energy resolution)
- These are all correlated.
  - To measure a cross-section need to divide out the flux and detection efficiency
  - To understand detection efficiency need to understand how to correctly distribute the event kinematics
- "Dead reckoning" these with Monte Carlos yields typical uncertainties of:
  - Flux: 20-30%
  - Cross-sections: 20-50% depending on modes
  - Detector response: ~50% for the long tails of PID distributions
- If one can place an identical detector in an identical beam, all three factors cancel in a near-far comparison leaving only the effects of oscillations

K2K Example: ν_μ-ν_e *Phys.Rev.Lett.96:181801,2006*

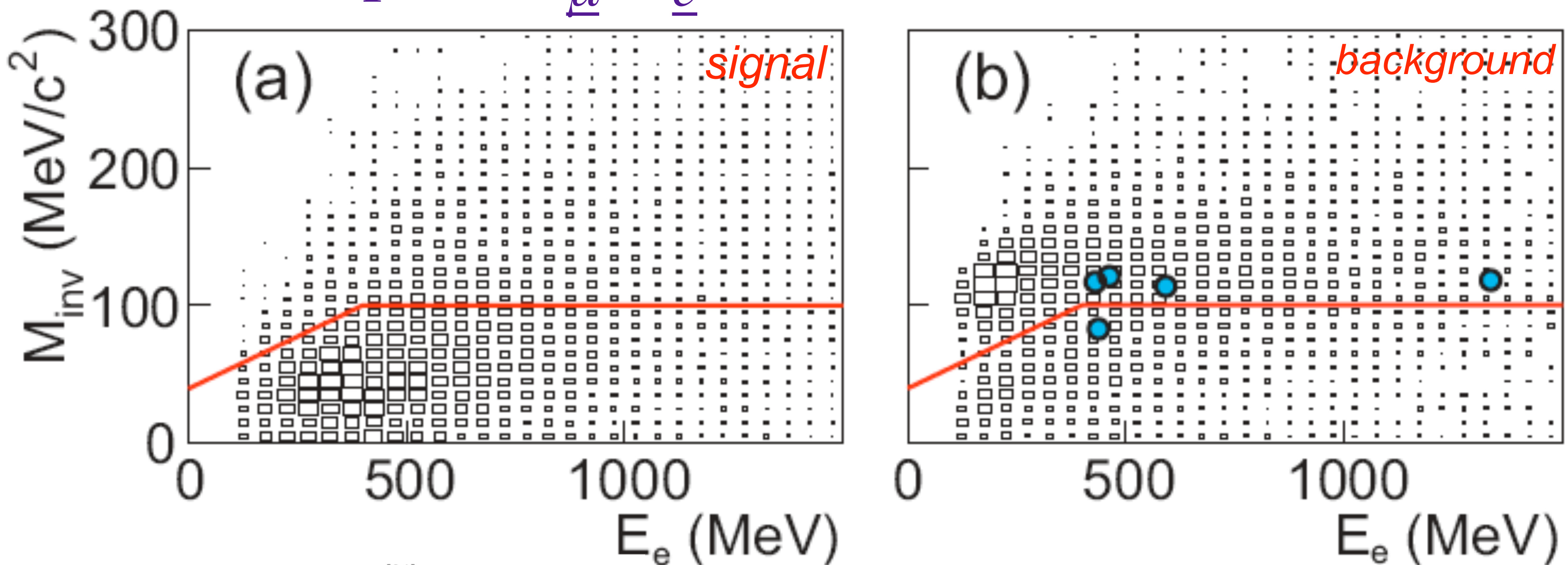


TABLE II: Systematic uncertainties [%] in the expectation of ν_μ-originated background. When estimating the total uncertainty, the correlations between the neutrino fluxes and the cross sections are taken into account.

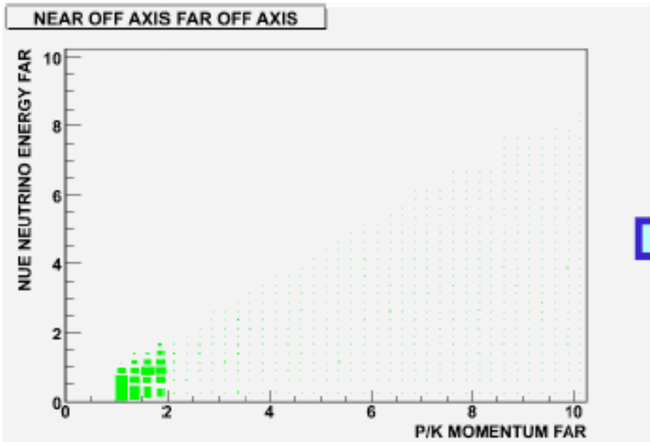
	K2K-I (Ia)	K2K-I (Ib)	K2K-II
NC1π^0/CC ratio	± 8	$^{+6}_{-7}$	$^{+6}_{-7}$
NC/CC ratio (non-NC1π^0)	± 4	± 3	± 3
π^0 energy spectrum	± 8		± 8
coherent π^0 model	$^{+3}_{-10}$		$^{+3}_{-10}$
π^0 mass cut	$^{+19}_{-18}$		$^{+19}_{-17}$
water properties	± 11		± 6
neutrino flux at SK	$^{+20}_{-17}$	± 6	± 6
non-QE/QE ratio	$^{+2}_{-2}$	$^{+1}_{-1}$	$^{+1}_{-1}$
detector efficiency	± 6		± 6
single electron selection	$^{+5}_{-7}$		$^{+7}_{-8}$
total	$^{+33}_{-32}$	$^{+37}_{-26}$	$^{+39}_{-24}$

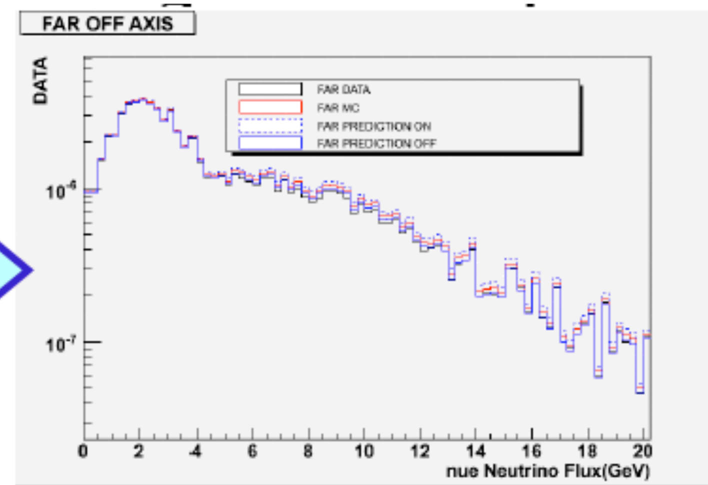
<u>~30% error on background *using near detectors*</u>

- 14% cross-sections
- 6% neutrino flux
- 22% detector response

Flux: Prediction of ν_e flux using on-axis measurement

Correlation matrix of production spectra to off-axis flux



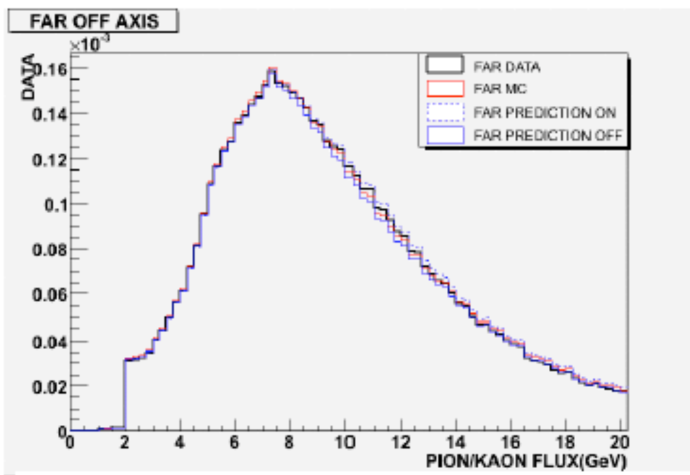


2D MATRIX

(NUE FLUX vs P/K Momenta (far))

1D VECTOR (NUE FLUX (far))

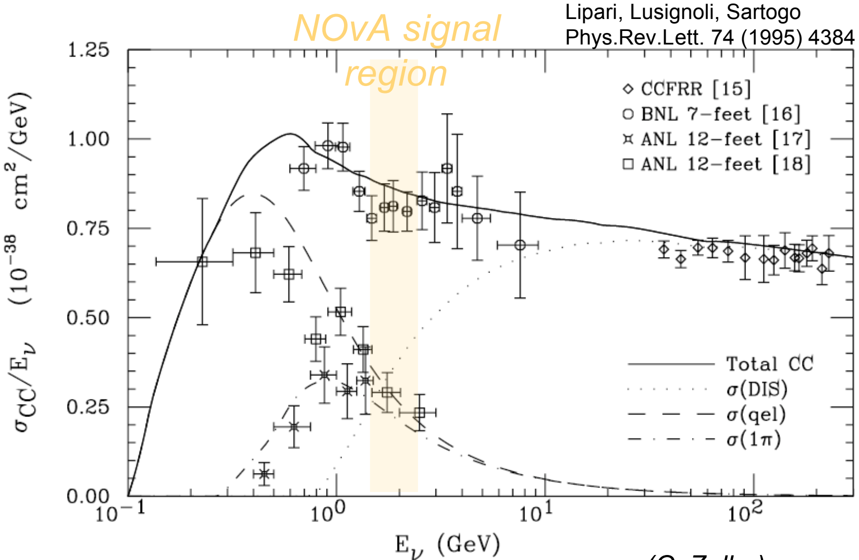
On-axis deconvolution of hadron spectrum

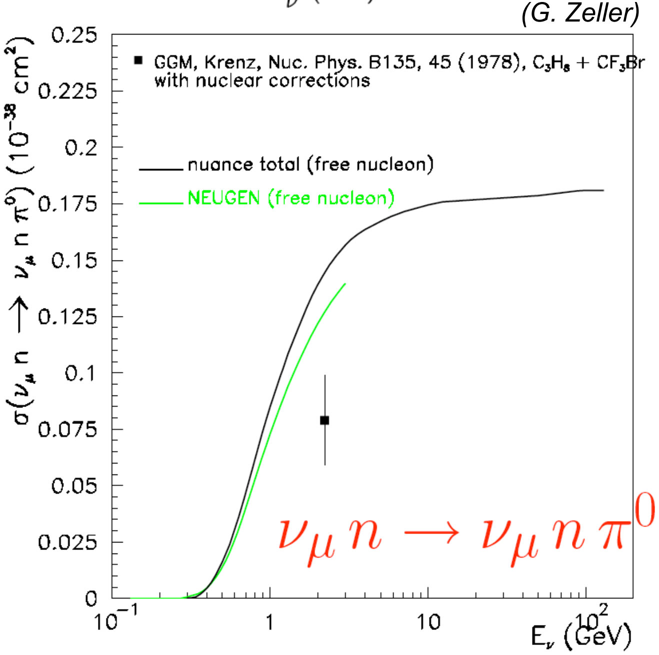


1D VECTOR (P/K Momenta (far))

- From Monte Carlos studies it seems possible to estimate the off-axis ν_μ and ν_e flux from an on-axis measurement to roughly 3%
- Study did not account for uncertainties in neutrino cross-sections (extrapolation from ~6 GeV to 2 GeV)
- Practical problem: instantaneous rates on-axis when operating at >1 MW
- Flux is only part of equation

Neutrino cross-sections

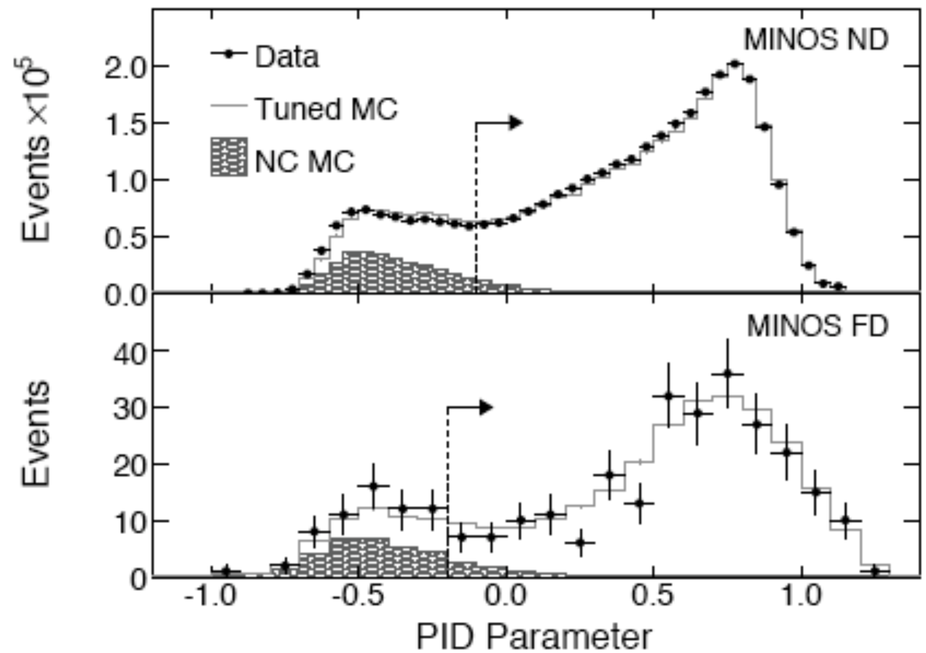


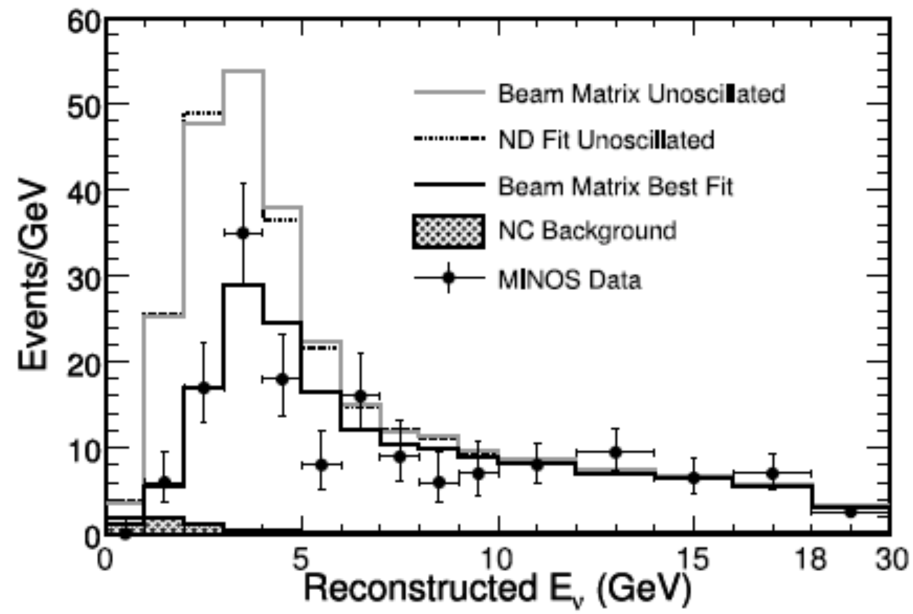


- 2 GeV is a tricky energy range for neutrino cross-sections
- Even best known cross-sections (CC-QE) have ~15-20% uncertainties
- Uncertainties for exclusive channels (for example NC single π^0 production, bottom left) are significantly larger
- MINERvA will help. But, how well can MINERvA measure NC cross-sections at 2 GeV in a wide-band beam which peaks at 3.5 GeV and has a long tail?
- …And of course, cross-sections are only one part of the story

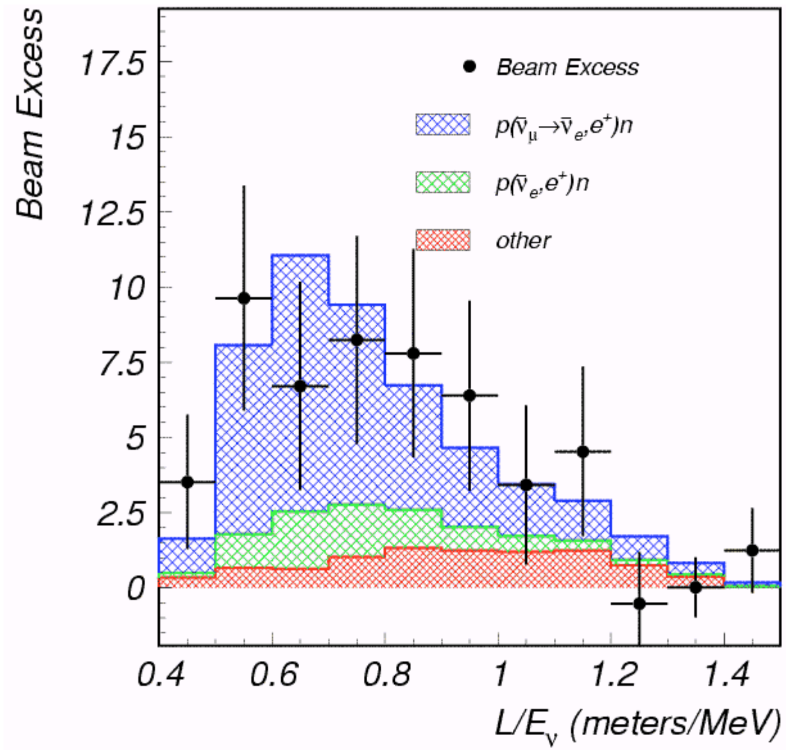
Detection efficiency

- To motivate my 50% estimate on the detection efficiency consider the MINOS ν_μ CC analysis.
- MINOS is optimized for muon detection, but small amount of NC leaks into the ν_μ CC sample
- MINOS estimates the uncertainty on the NC leakage into the ν_μCC sample to be +/-50%
- Small effect on oscillation measurement as ND and FD rates are very nearly 100% correlated and ν_μ CC rate is large
- NOvA doesn't expect nearly as large a signal as MINOS





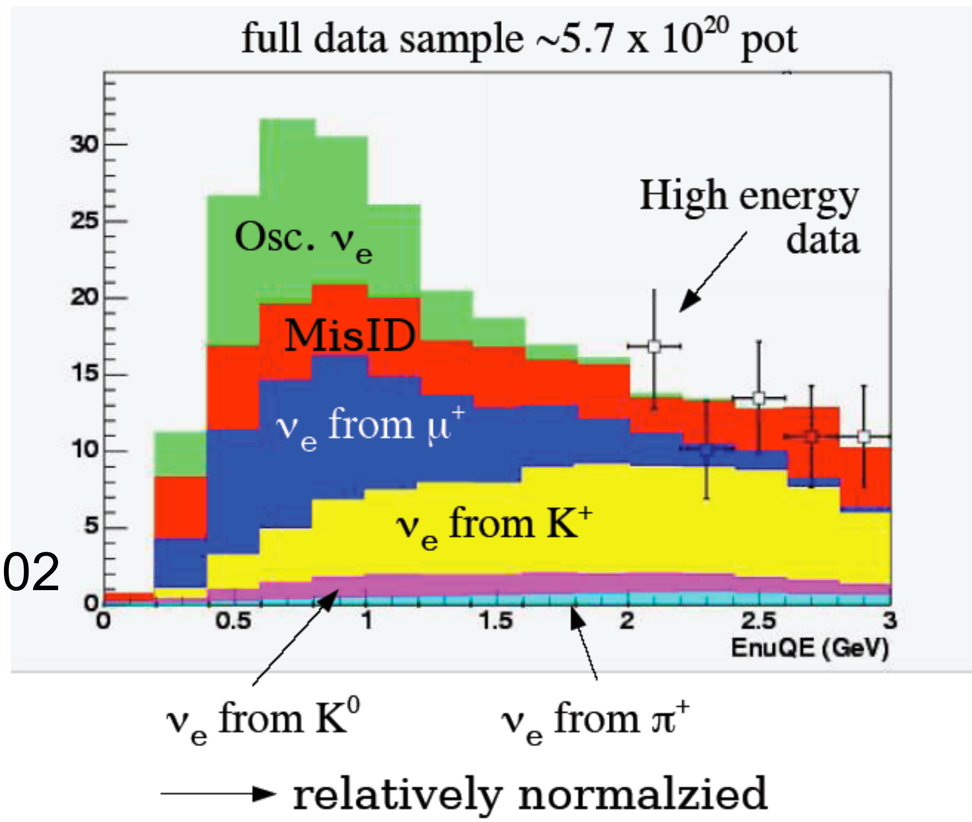
The LSND and MiniBooNE examples



$87.9 \pm 22.4 \pm 6.0$

events above beam backgrounds

3.8σ discovery?



MiniBooNE started data taking in 2002
Working to reduce uncertainties in background to acceptable levels
- Cross-sections: ~20%
- Flux: ~50% ⏩20% w/ HARP data
- Detector response: ~50% ⏩20% (??)

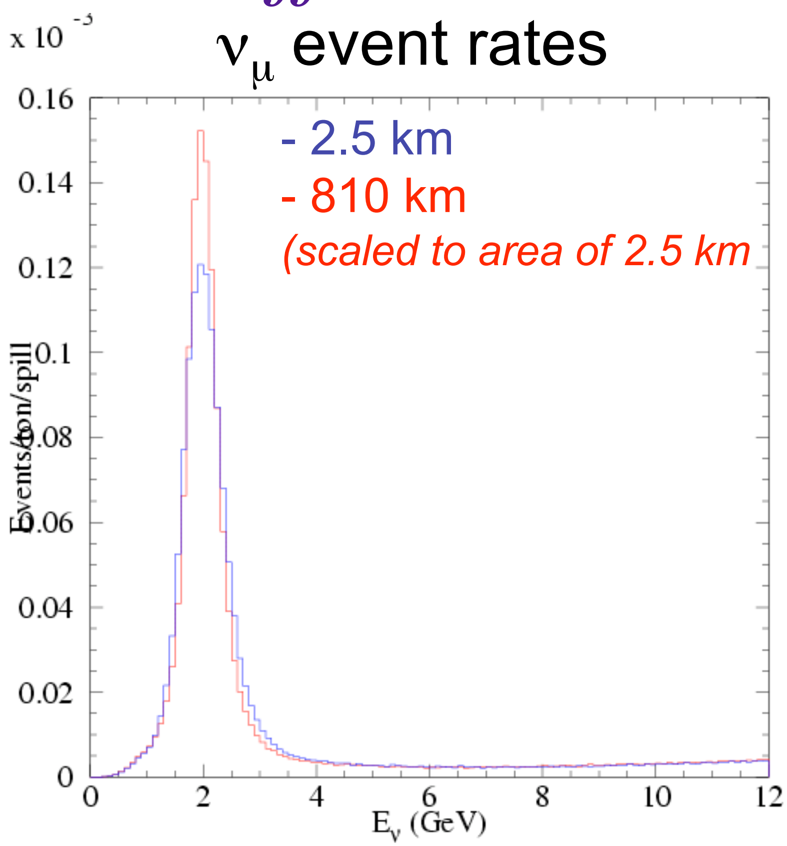
Why NOvA needs an off-axis near detector

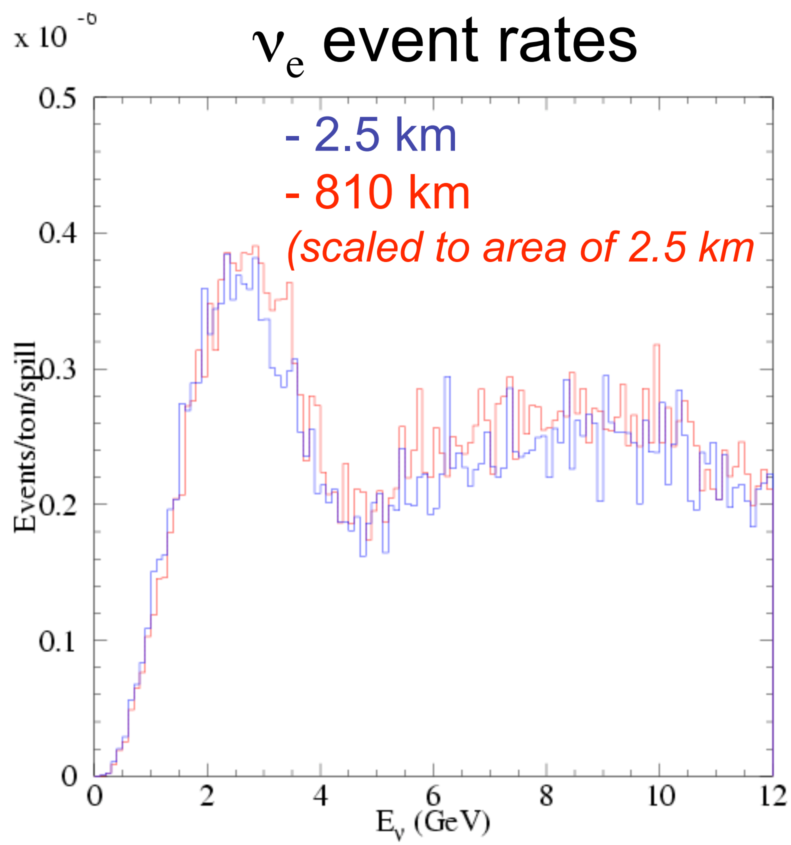
- To reach NOvA's goal of a 3-sigma observation of non-zero $\nu\mu$-νe oscillations at the atmospheric length scale we need to control systematic uncertainties in the background estimate below 10%
- The backgrounds to the NOvA νe search come 1/2 from the intrinsic νe component of the beam and 1/2 from rare (1:500) NC events which fake a νe signal
- Uncertainties from the neutrino flux, the interaction cross-sections, and the detector response are all order 10-50%
  - On-axis measurements of the $\nu\mu$ CC rate (say by MINOS, MINERvA,…) may allow prediction of off-axis flux, but not cross-sections or NOvA detector response
  - On-axis measurements of neutrino cross-sections do not give any information about the rate at which the NOvA detector tags NC and $\nu\mu$-CC events as νe signal events
  - Only an off-axis measurement of the response of a NOvA detector measures the correct product of flux x cross-section x detector response allowing the goal of <10% uncertainty in background to be reached
- NOvA near detector has other benefits:
  - Faster results
    - Reduction of systematic error by 10% is like gaining 20% in exposure
    - Large control sample of interactions for study: faster understanding of detector
  - Better analysis:
    - Near detector is the only monitor of the off-axis neutrino beam
    - Ultimate reach of experiment improves proportionally to the size of the systematic error on the background

Ideal case

- Ideally one would expose a detector which is identical to the far detector to the same beam at a location where the oscillation probabilities are negligible
  - Same beam: same flux, same cross-sections
  - Identical detector: same efficiencies, same cross-sections
- Differences in the event rates seen in the two detectors could then be ascribed to oscillations
- *Important Caveat:* Even in the ideal case, the near detector is much more sensitive to the ν_μ–CC to e-like fake rate than the far detector as the ν_μ-CC component is not oscillated away at the near site. This difference between near and far is mitigated by ensuring that this fake rate is as small as possible
- This ideal case can be nearly achieved by placing the near detector at a distance large compared to the 670 m length of the NuMI decay pipe

Spectra off-axis at z=2.5 km

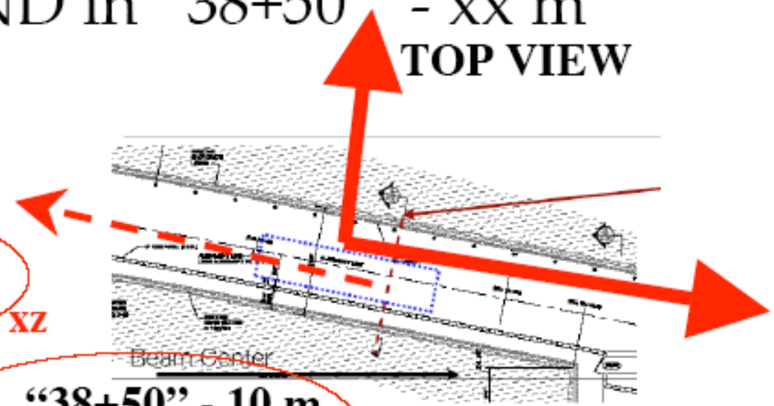


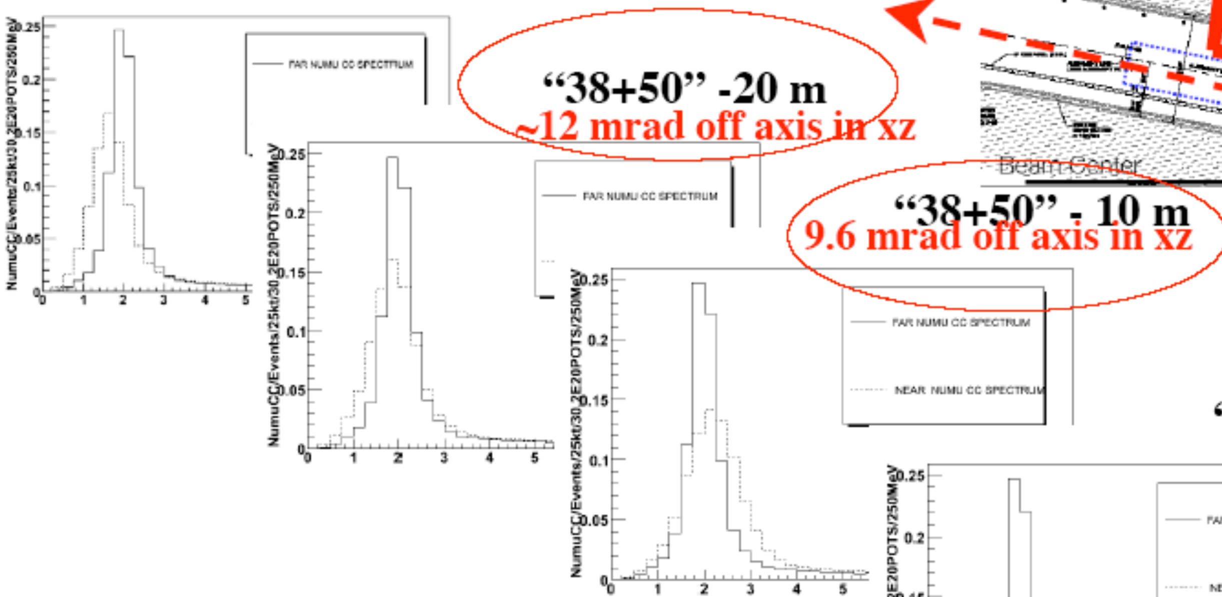


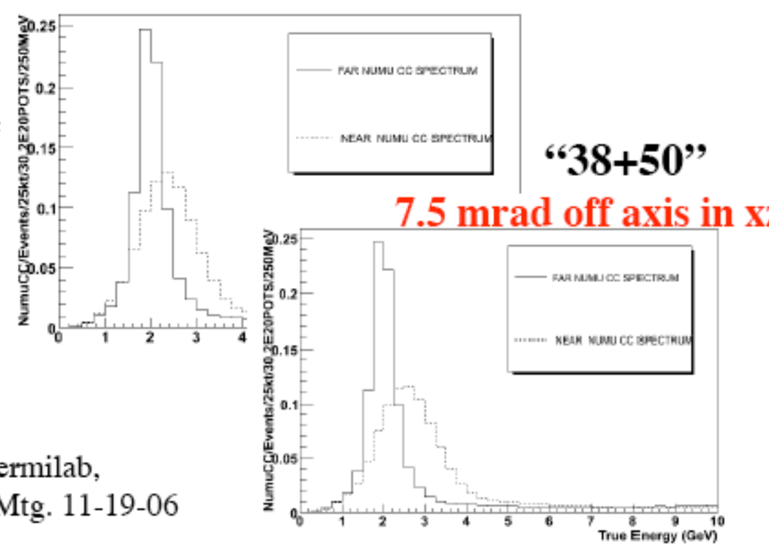
- This is the most distant location on the Fermilab site. It would be between 100 and 130 m underground
- Flux, cross-section, and detection efficiencies would very nearly cancel, leaving only oscillation to cause near-far differences
- Added benefit: Event rate would be ~1 interaction per spill eliminating overlap problems
- However, there are sites available in NuMI tunnels that give reasonable matches to the Ash River fluxes

Numu CC Spectrum : ND in "38+50" - xx m

Moving Upstream…





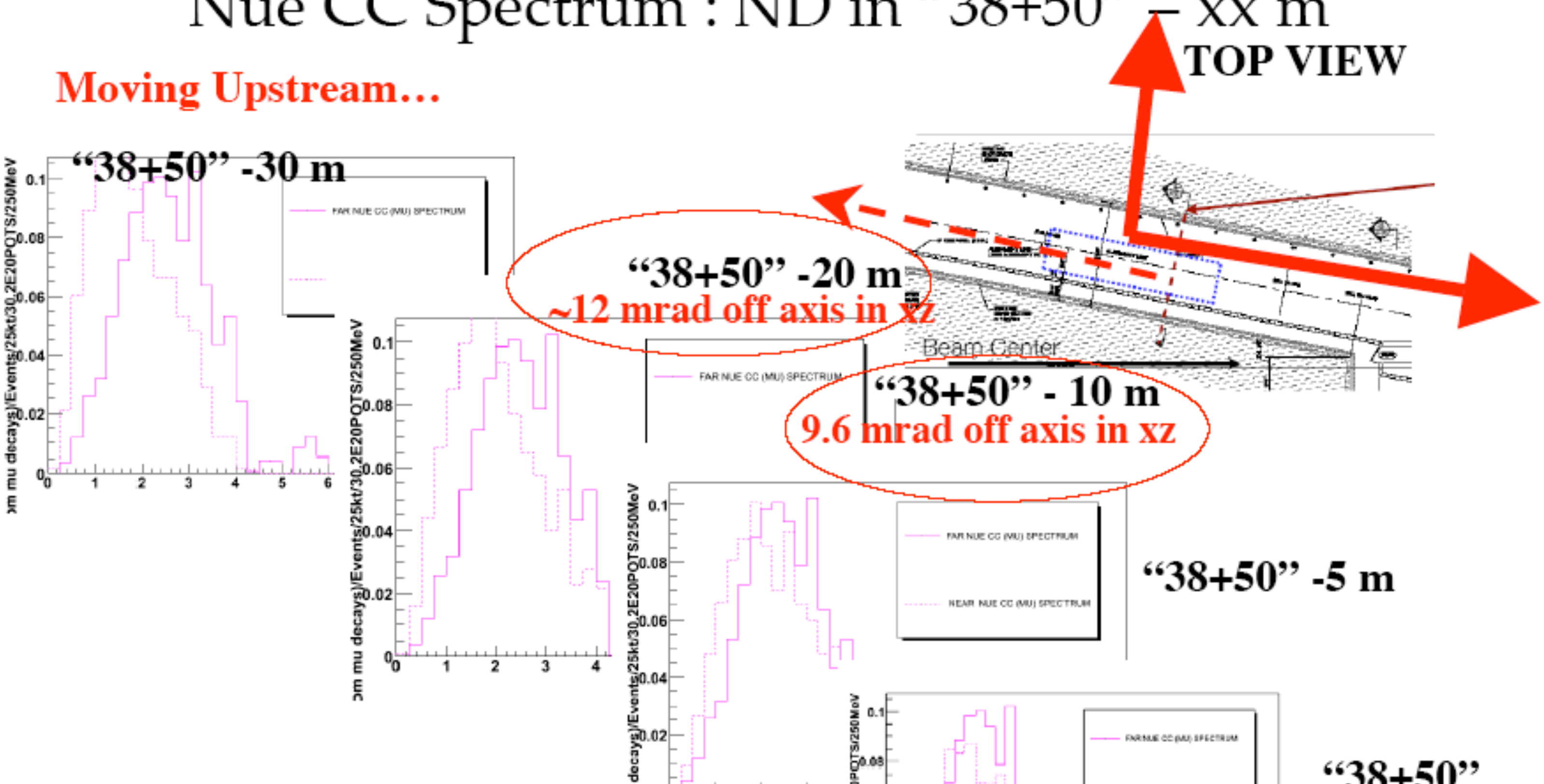


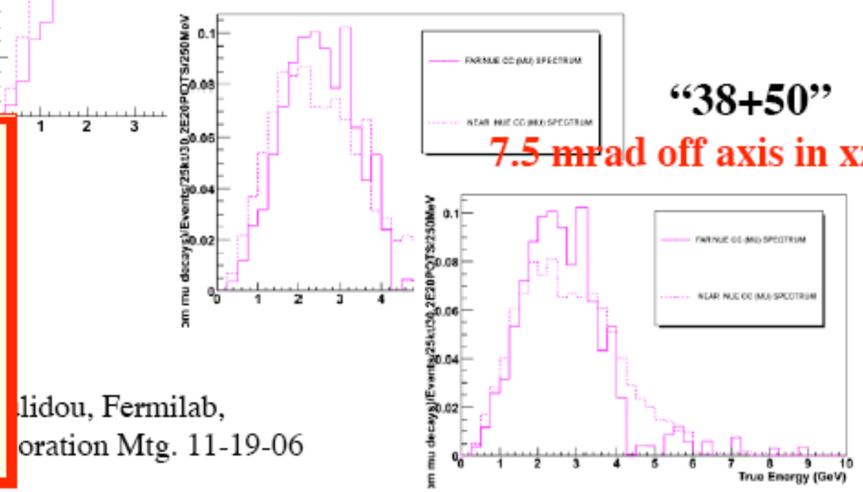
- *Numu CCs*
- *Far detector : Black continuous line, Near detector : Black Dashed Line*
- *Moving upstream between 10 and 20 m is producing a ND spectrum closer to the FD one.*

lidou, Fermilab,
oration Mtg. 11-19-06

Nue CC Spectrum : ND in "38+50" – xx m

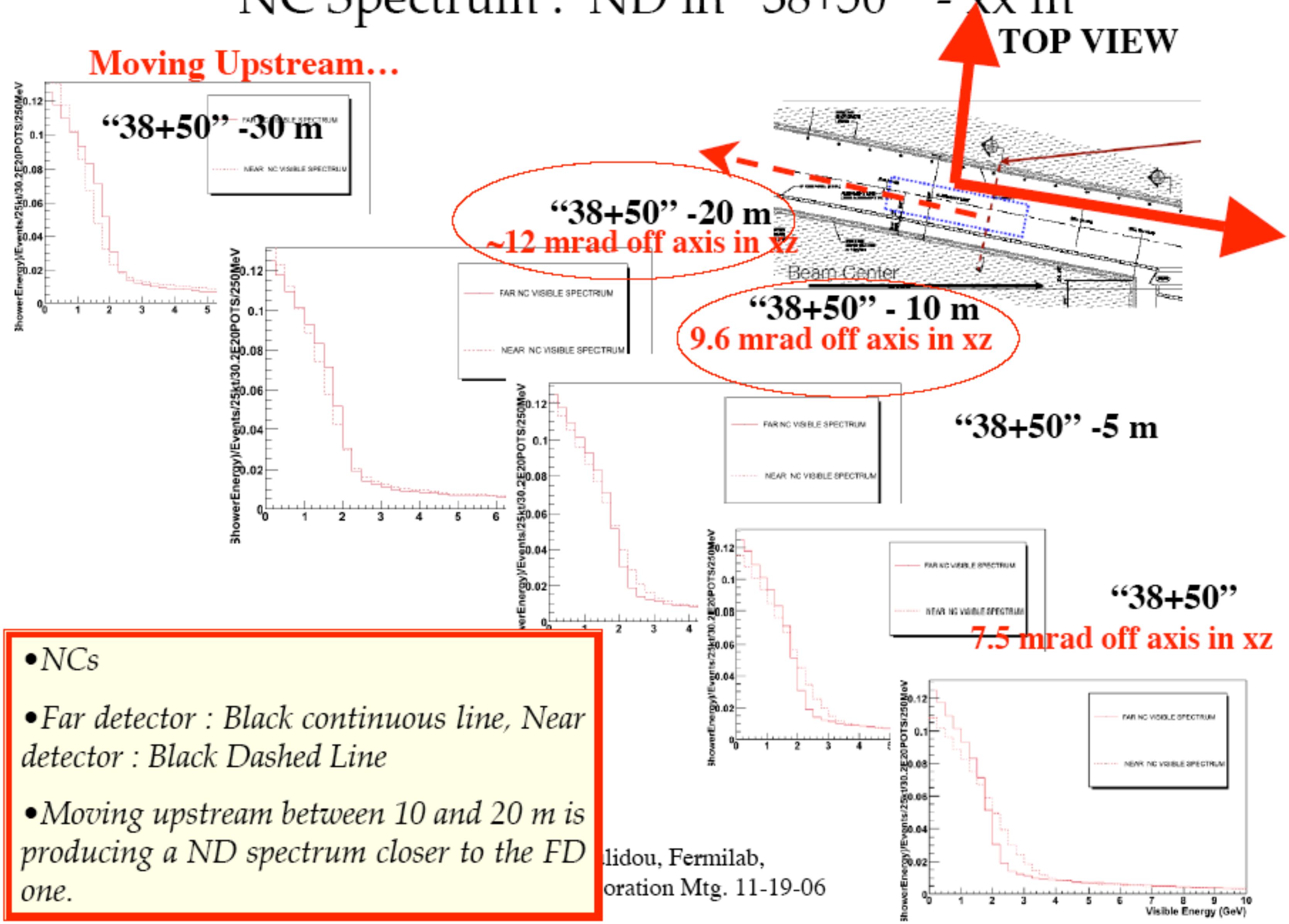
Moving Upstream…





- *Nue CCs (from muon decays, different kinematics, comes from muon decays)*
- *Far detector : Black continuous line, Near detector : Black Dashed Line*
- *Spectra more similar in "nominal" location*

NC Spectrum : ND in “38+50” - xx m



- *NCs*
- *Far detector : Black continuous line, Near detector : Black Dashed Line*
- *Moving upstream between 10 and 20 m is producing a ND spectrum closer to the FD one.*

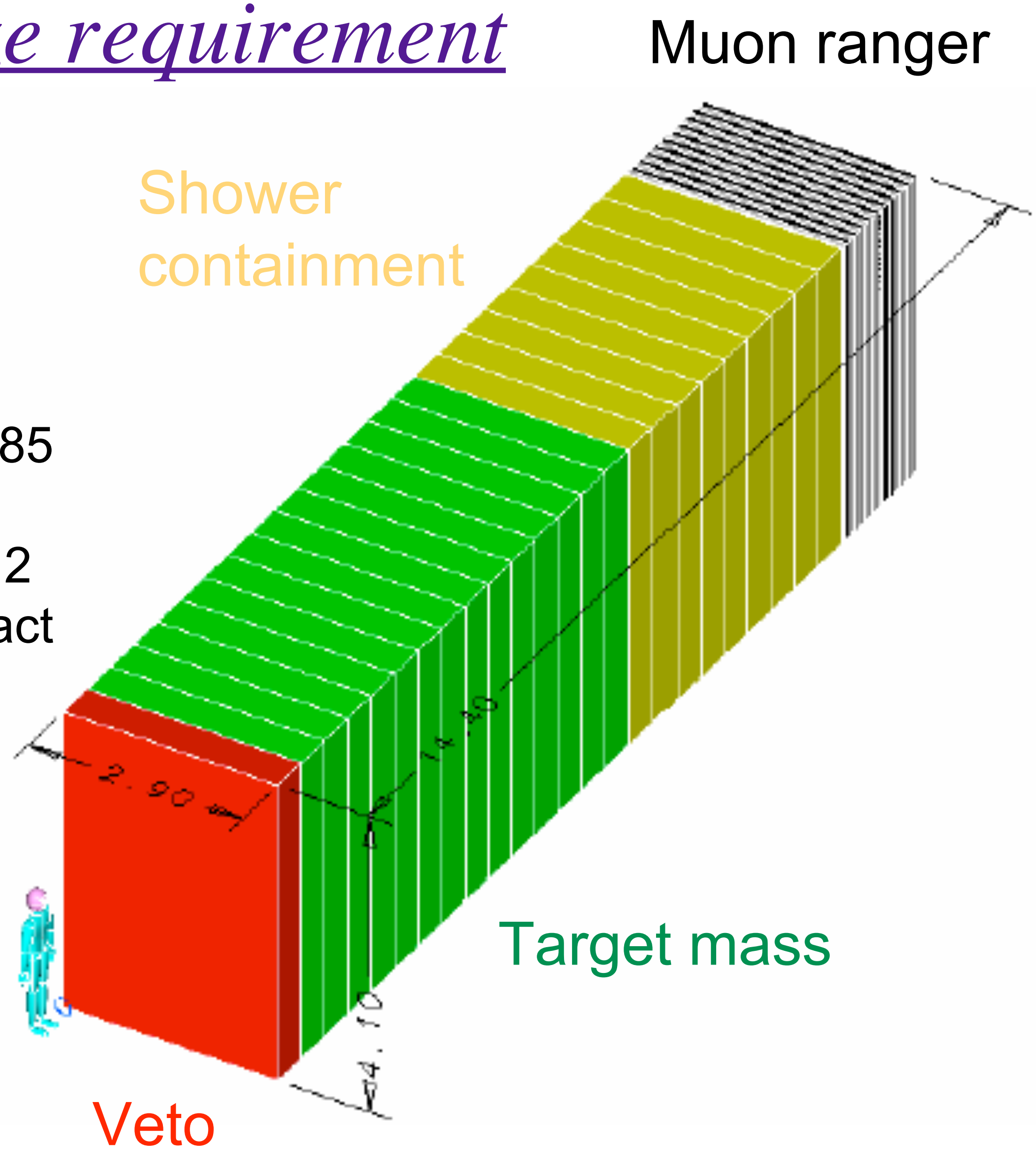
Near detector size requirement

- Would like roughly 2000 ν_e CC events in 1 year of running. Allows ~2% measurement of total rate in given set of beam conditions and enough statistics to make distributions
- 20 tons of fiducial mass to achieve this
- This is a volume of NOvA detector 3 m on a side
- Radiation length in NOvA detector is 44 cm. Moliere radius is roughly 10 cm
  - To contain shower longitudinally requires 10 radiation lengths (4.4 m)
  - To contain shower on sides requires ~5 R_M (50 cm)
- So a cubic fiducial volume leads to a detector 5 x 5 x 7 meters in size

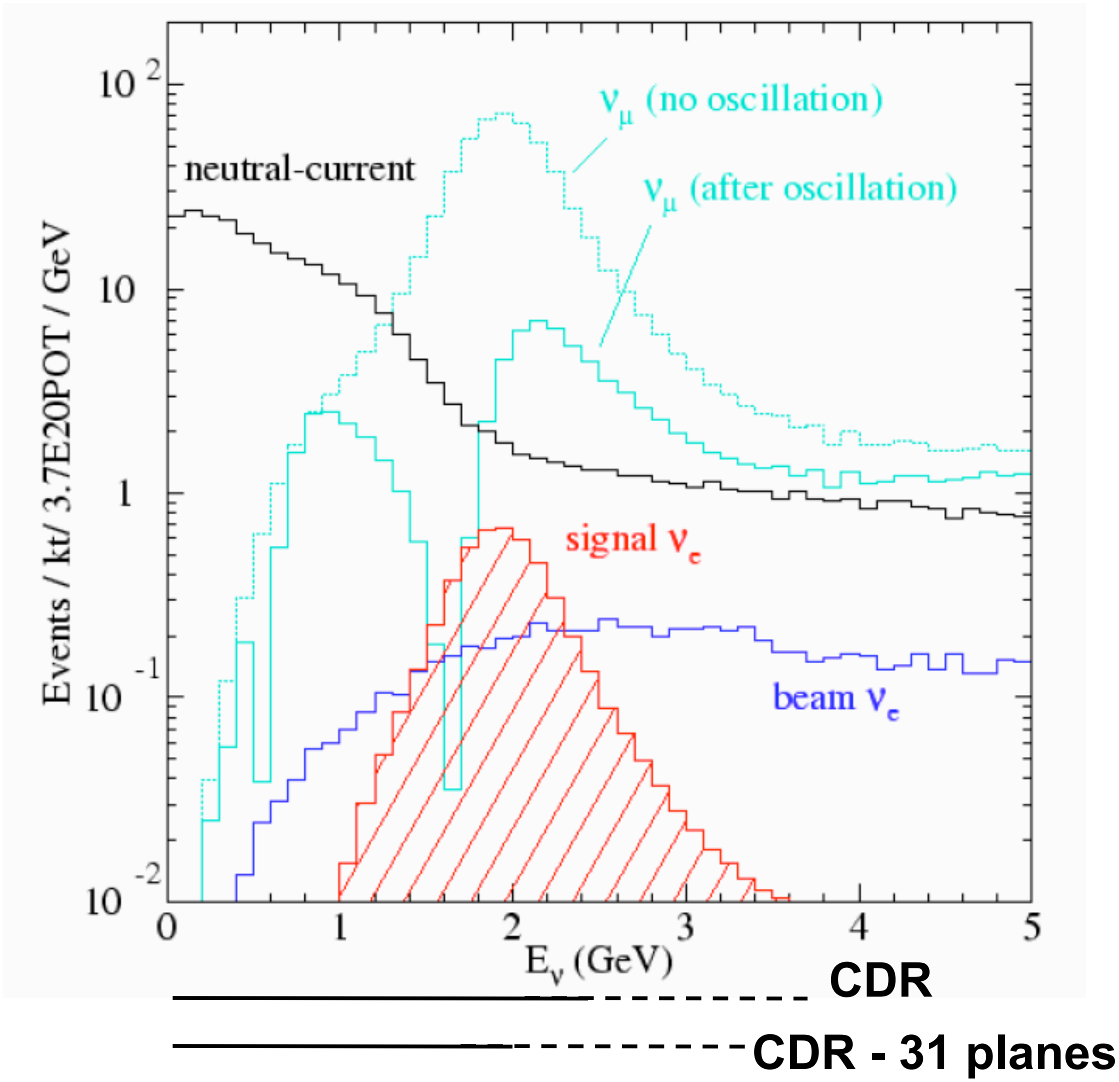
Near detector size requirement

Accommodate size constraints from the tunnel

- Make fiducial volume thin, but long: 1.65 x 2.85 x 7.4 m
- Use iron to range out 2 GeV muons in a compact way



Length required for muon containment



For ν_μ disappearance measurement we want to measure the unoscillated ν_μ rate over the dip region

For the CDR Near Detector:

- Muon range before the muon ranger is 975 to 2400 MeV
- Muon range with the muon ranger is 2425 to 3925 MeV

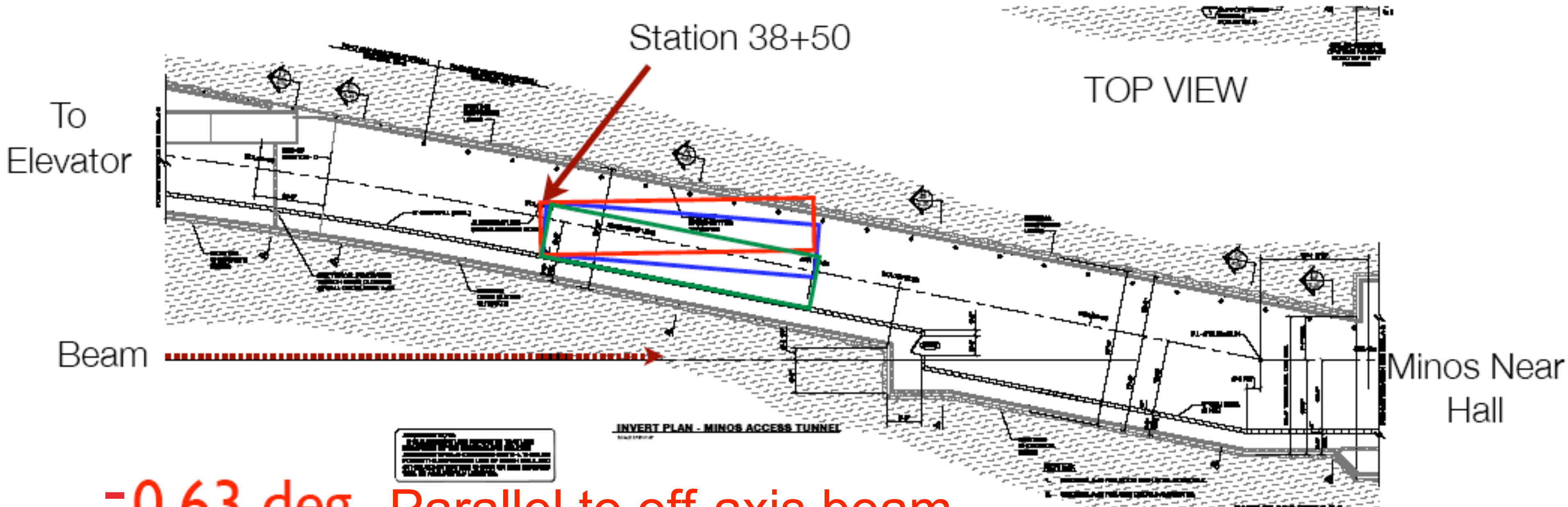
CDR-1 block of 31 planes from the fiducial region:

- Muon range before the muon ranger is 975 to 1975 MeV
- Muon range with the muon ranger is 2425 to 3500 MeV

Near detector angle

- Previous slides show that there are locations in the access tunnel that provide a good match to the ν_μ, ν_e, and NC spectra.
- Have to accept some constraints on the geometry of the detector imposed by the tunnel
- Orientation of detector with respect to beam
  – Tunnel wall runs at 11^o to the beam axis
  – If we rotate detector as far as it will go in tunnel remaining angle is 5^o to the beam axis and the detector blocks the tunnel

Near detector orientation



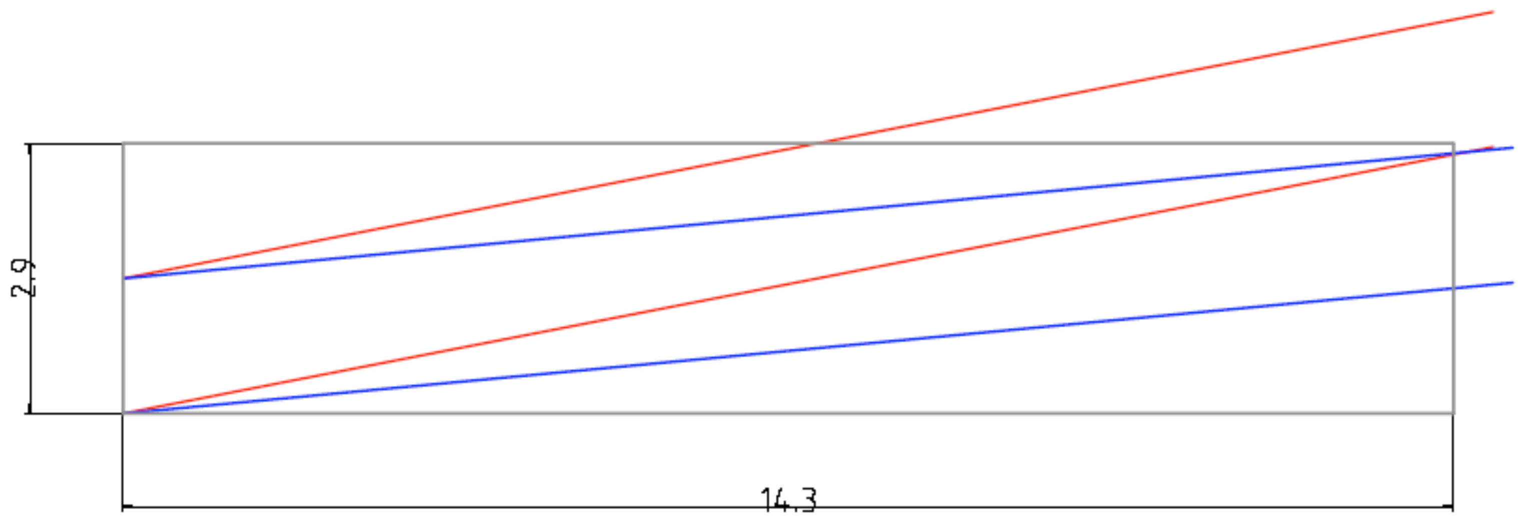
-0.63 deg Parallel to off-axis beam

5.73 deg Maximum rotation w/o digging

11 deg Parallel to tunnel

Near detector angle: muon containment

This long, narrow detector has a problem for muon containment

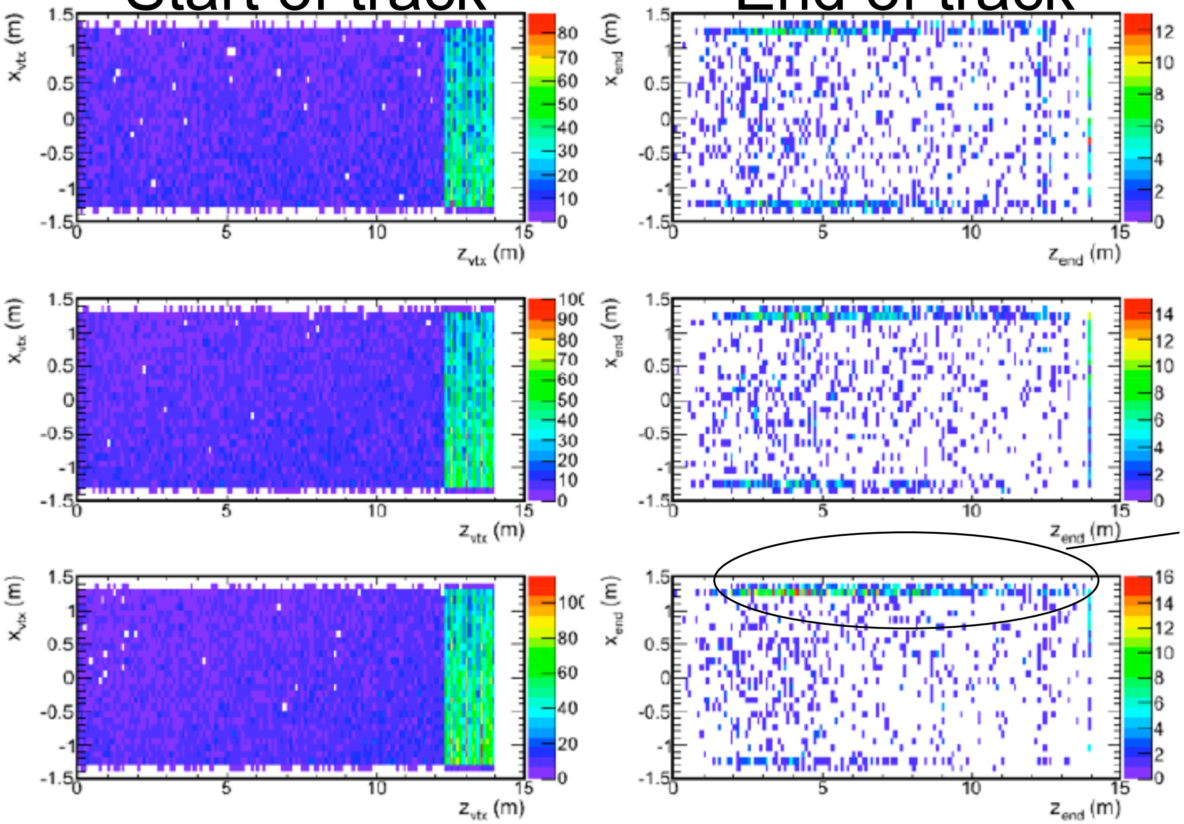


Red: Tracks entering at 11^{o} to detector face.

Blue: Tracks entering at 5^{o} to detector face

Near detector angle: muon containment

Start of track   End of track



0.63 deg

5.37 deg

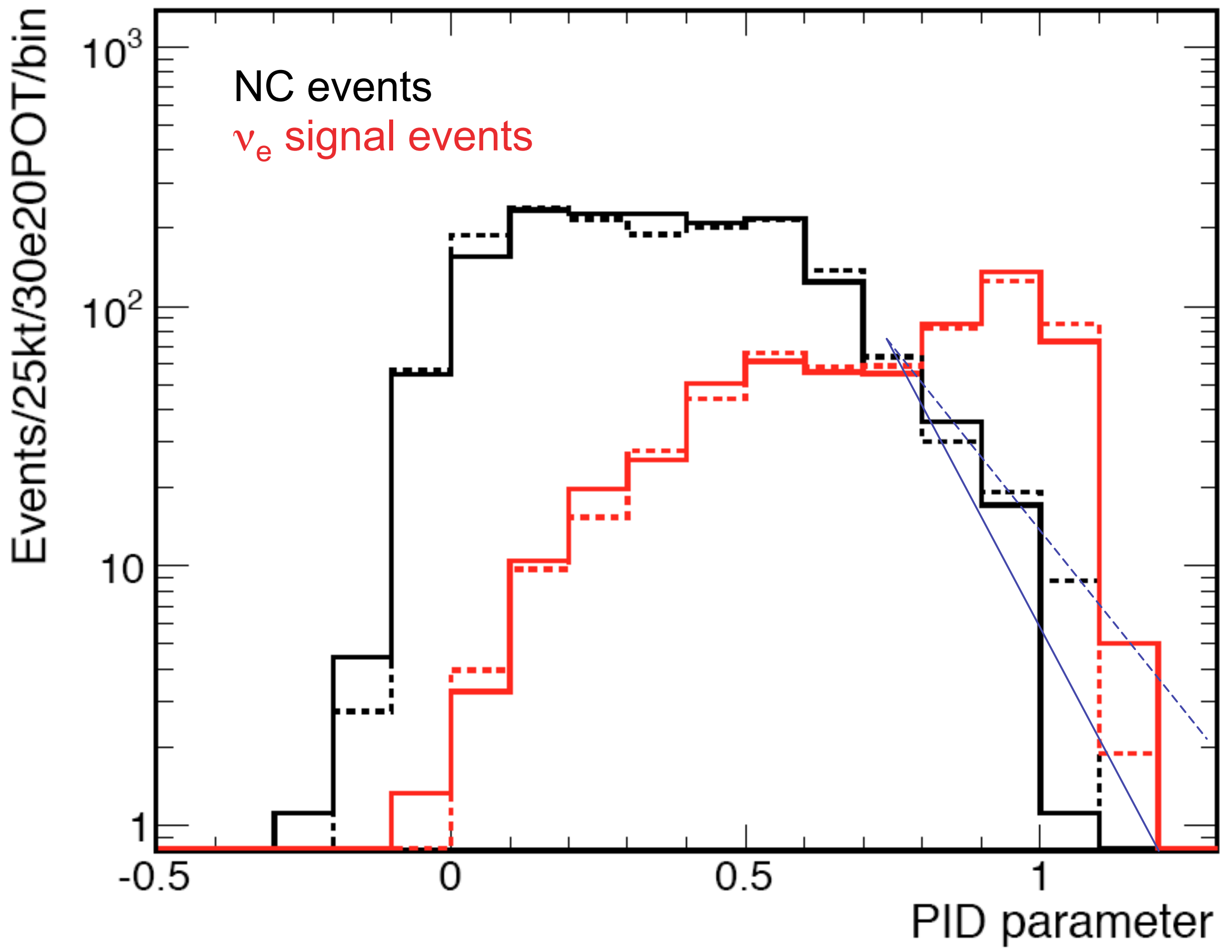
Muons leak out the side
Very few exit the back

11 deg

Orientation	Exit Sides	Exit Back	Ratio
0.63 deg	847	110	7.70
5.73 deg	885	113	7.83
11 deg	835	43	19.41

Particle ID in a rotated detector

- Test performance of particle ID in a rotated detector 5 degrees wrt to beam
- Differences shown for NC backgrounds. Solid is non-rotated detector, dashed is rotated detector
- Summarized in table on next slide



Particle ID in rotated detector

- In far detector rotated 5^{o} to the beam (#'s in parenthesis):

	PID eff.	Total eff.	No. accepted
nu_e signal:	0.367 (0.387)	0.288 (0.301)	208.7 (218.3)
nu_mu CC:	0.002 (0.003)	0.001 (0.001)	1.7 (2.22)
NC:	0.010 (0.018)	0.002 (0.004)	15.1 (26.9)
nu_e BG:	0.272 (0.244)	0.095 (0.079)	15.5 (13.0)
All BG:	0.013 (0.019)	0.004 (0.005)	32.3 (42.1)

- Effect on *near or far* detector performance:
  - Muon tracking efficiency ~1% lower
  - NC rate increases 70% relative to signal
  - ν_μCC rate increases 80% relative to signal. Issue for near detector where ν_μCC rate is 10x higher
  - FOM for ν_e appearance drops from 36.7 to 33.7
- We could eliminate the near/far difference by rotating the far detector, but...
  - 1% of detector mass is ~\$2M, 1% of Anu upgrades is ~\$0.6M
  - Gaining 9% in FOM requires 18% more exposure. Equivalent to ~\$36M in detector mass or ~\$10M of Anu upgrades
- If near detector is rotated and far detector is not, then we have to make ~70% corrections to the rates measured at the ND

Near detector angle summary

- 11 degrees is bad for muon containment
- 5 degrees may be acceptable, however:
  - See significant change in NC/signal rates which would have to be corrected near to far
  - We block the tunnel (John's talk has more about options)
- *"Risk management":* Judgement of collaboration was that it is worth up to ~0.5 kt of far detector mass to get this angle right, reduce the systematic error on the background and not rely on Monte Carlo to predict the tails of the PID distributions correctly
- Our preferred option is the cheapest: do the minimum excavation required to rotate to the correct angle